

Surface Gravity Waves and Coupled Marine Boundary Layers

Peter P. Sullivan

National Center for Atmospheric Research

Boulder, CO 80307-3000

Phone:(303) 497-8953 fax:(303) 497-8171 email: pps@ncar.ucar.edu

James C. McWilliams

Department of Atmospheric Sciences and

Institute of Geophysics and Planetary Physics, UCLA

Los Angeles, CA 90095-1565

Phone:(310) 206-2829 fax:(310) 206-5219 email: jcm@atmos.ucla.edu

Chin-Hoh Moeng

National Center for Atmospheric Research

Boulder, CO 80307-3000

Phone:(303) 497-8911 fax:(303) 497-8171 email: moeng@ncar.ucar.edu

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LONG-TERM GOALS

The long term objective of our research is to advance the understanding of air-sea interaction and the coupling between the atmospheric and oceanic boundary layers (the ABL and OBL) mediated by the surface gravity wave field, in order ultimately to develop better parameterizations of the boundary layers and surface fluxes for coupled, large-scale numerical models. Turbulence-resolving, large-eddy and direct numerical simulations (LES and DNS) are the main tools to be used to investigate interactions among the ABL, OBL, and the air-sea interface. Using numerically generated databases, we intend to investigate: (1) vertical heat and momentum fluxes carried by wave-correlated winds and currents; (2) enhanced small-scale, turbulent energy, mixing, and dissipation due both to enhanced wave-correlated wind and current shears and to wave breaking; and (3) wave-averaged influences due to mean Lagrangian currents (Stokes drift) that give rise to coherent Langmuir circulations in the ocean. These mechanisms will be considered for a variety of surface wave states. Finally, we intend to make an effort to connect our simulation results with the proposed Coupled Boundary Layers Air-Sea Transfer (CBLAST) field campaigns.

OBJECTIVES

Our recent research objectives have focused on understanding the interaction between an imposed surface gravity wave and stratified turbulence in the ABL and OBL, and generating LES of the CBLAST low-wind site using typical large-scale forcings.

APPROACH

We are investigating interactions among the ABL, OBL, and the connecting air-sea interface using both LES and DNS. The premise behind this approach is that the fundamental processes that lead to air-sea coupling will manifest themselves in three-dimensional, time-dependent simulations. Hence, the creation of sufficient numerical databases will allow for the interpretation of air-sea interaction. The LES code adopted for our work evolves from the efforts of Moeng (1984), Sulli-

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van *et al.*(1994), Sullivan *et al.*(1996), and McWilliams *et al.*(1997). The spatial discretization in our LES is pseudospectral in horizontal directions and finite difference in the vertical, with third order Runge-Kutta time stepping. A novel nesting procedure allows for fine nested meshes to be embedded within an outer coarse grid. A recently developed DNS code that accommodates a temporally and spatially varying lower boundary (Sullivan *et al.*, 1999; Sullivan *et al.*, 2000) is also being extensively used. DNS has served a dual role in our research; it provides a clean framework for testing LES developments, and the DNS results have provided insight into flow over moving surface gravity waves.

WORK COMPLETED

During the past fiscal year we attended and presented results at two CBLAST PI meetings, completed and submitted an archival manuscript describing the findings from our DNS study of the interaction between surface gravity waves and stratified turbulence (Sullivan & McWilliams, 2001), and performed preliminary LES of the ABL and OBL at the low-wind CBLAST field site. The emphasis here is on reporting results from the latter activity.

The objectives of our LES site simulations are twofold: to gain physical understanding into the evolution of the low-wind ABL and also to provide insight as to the expected structure of the ABL for future field campaigns. In order to tailor the LES to the CBLAST low-wind site, our atmospheric LES code was modified to accept both spatial and temporal variations in the large-scale forcing conditions, *i.e.*, the geostrophic winds were allowed to vary with time and height above the water surface. The geostrophic winds as well as the sea surface temperature were derived from output of the mesoscale code COAMPS. Essentially a one-way coupling between the COAMPS code and the NCAR LES was performed. The COAMPS simulations (carried out at NRL Monterey) were centered on the CBLAST low-wind site and used three nested meshes with a horizontal resolution of 1.5km in the finest mesh (a variable vertical grid was used). We should note that the resolution in the finest COAMPS grid is still inadequate to capture small scale turbulent motions in the ABL. To test sensitivity to domain size the LES used a small domain of $(2 \times 2 \times 0.8)\text{km}^3$ with $(100 \times 100 \times 96)$ gridpoints with a resolution of $(20 \times 20 \times 8.3) \text{ m}^3$ and a three times larger horizontal domain of $(6 \times 6 \times 0.8)\text{km}^3$ with $(200 \times 200 \times 96)$ gridpoints. Each of the LES employed more than 10,000 timesteps and resulted in 8 hour simulations of the atmospheric ABL. For the time and space scales considered in the LES the sea surface temperature was held fixed at 297.2 K. Further details of the subgrid-scale (SGS) model and numerical methods used in the LES are described in Sullivan *et al.*(1994) and Sullivan *et al.*(1996).

Our simulations of the OBL are less site specific in part due to the lack of detailed information about the large-scale forcing conditions. The primary new addition to the OBL code is an option for a no-slip rigid boundary at the bottom of the LES domain. The latter boundary condition is appropriate since the water column at the CBLAST site is only 20 meters deep. Several OBL simulations were carried out using $(100 \times 100 \times 96)$ gridpoints in a computational domain of $(50 \times 50 \times 20)\text{m}^3$ (hence the resolution is $(0.5 \times 0.5 \times 0.2)\text{m}^3$). A constant wind stress ($\tau = 0.05 \text{ Nm}^{-2}$ or $u_* = 0.007 \text{ m/s}$) and small surface heat flux into the ocean ($q_* = -5 \text{ Wm}^{-2}$) were imposed with an initial mixed layer depth $h = -5\text{m}$. Wave influences were included by adopting the Craik-Leibovich assumptions as described in McWilliams *et al.*(1997) with a turbulent Langmuir number $La_t = 0.5$. This is weaker wave forcing than used in McWilliams *et al.*(1997). For $u_* = 0.007 \text{ m/s}$, $La_t = 0.5$ corresponds to a waveslope $ak = 0.05$ for waves of length $\lambda = 76.5\text{m}$. A suite of simulations was performed by varying the strength of the stratification N^2 below the mixed layer depth. N varied from $4.4 \cdot 10^{-3}$ to $2.2 \cdot 10^{-2} \text{ s}^{-1}$. All runs used 10,000 timesteps which result in simulations of approximately 6.8 hours.

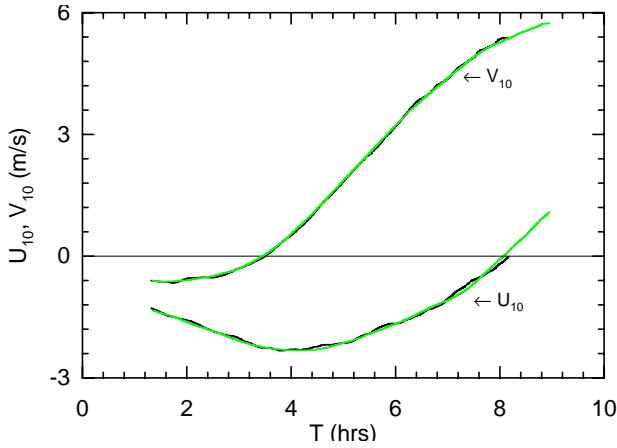


Figure 1: Typical average winds at $z = 10$ meters above the water surface at the CBLAST low-wind site. Results from small (large) horizontal LES domains are shown in black (green).

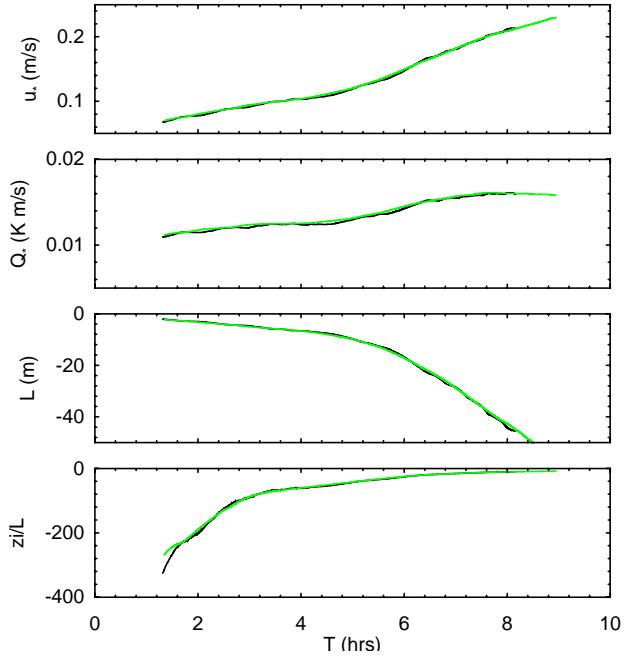


Figure 2: Friction velocity u_* , surface heat flux q_* , Monin-Obukov length L , and stability parameter z_i/L at the CBLAST low-wind site. Black and green curves correspond to small and large horizontal LES domains.

RESULTS

The time varying geostrophic winds (*i.e.*, large scale pressure gradients) imposed by the mesoscale model on the LES lead to a continual evolution of the turbulent flowfields in the ABL. This is illustrated in Figure 1 where the components of the average winds at 10 meters (U_{10}, V_{10}) above the water surface are shown. Here the average winds in the LES (as well as other statistics) are obtained by spatial $x - y$ averaging at any particular instant in time and vertical location z . Early in the simulations the winds are mainly from an easterly direction and weak, $|U_{10}| < 2$ m/s. As time progresses the winds increase in strength and are dominated by a southerly component. We should note that this is the anticipated wind direction and magnitude for the CBLAST field campaign. Typical statistics in the surface layer of the ABL further highlight the dependence on the large scale forcing (see Figure 2). The surface heat flux is small and positive ($10 < q_* < 18$ W m⁻²) while the surface friction velocity varies by more than a factor of two over the duration of the simulation. Thus because of the dependence on u_* , the Monin-Obukov length $L = -u_*^3/\beta q_* \kappa$ (where β is the thermal expansion coefficient and κ is the von-Kármán constant) experiences a significant variation with time. The stability of the ABL then has wide variability even with relatively weak winds. For example, the non-dimensional stability parameter z_i/L (z_i is the ABL height) varies from -300 to -5. Notice that all of our statistical results are nearly identical for the two different computational domains suggesting that the simulations adequately capture the large scale components of the flow. Snapshots of the instantaneous w flowfield, shown in Figures 3 and 4, provide dramatic evidence of the impact of atmospheric stability on the turbulent structures in the ABL for the weak winds considered. For $z_i/L = -240$ the dominant structure is a closed hexagon shaped cell typical of Rayleigh-Bénard convection (*e.g.*, Moeng & Rotunno (1990)). As

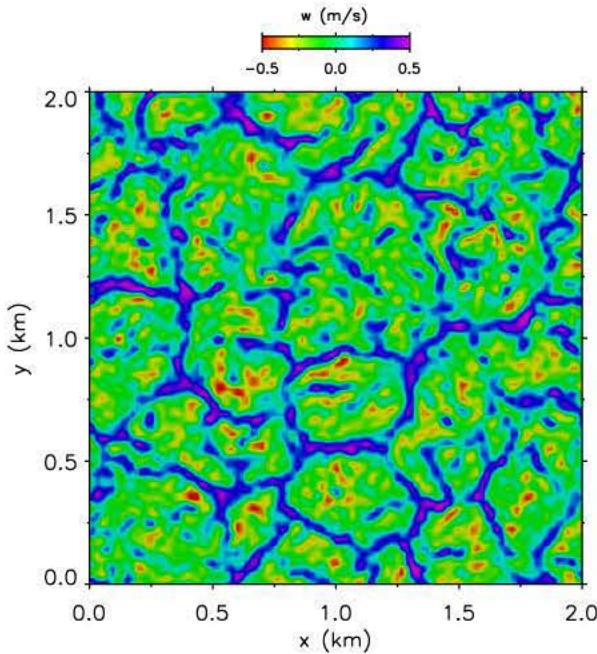


Figure 3: Snapshot of the vertical velocity field at $z = 25$ meters above the surface at $t = 1.5$ hrs with $z_i/L = -240$. Note the formation of closed Rayleigh-Bénard cells.

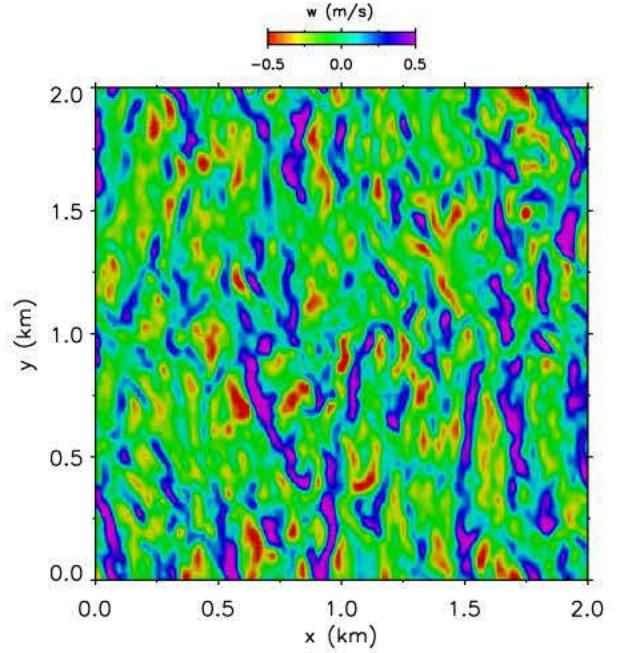


Figure 4: Snapshot of the vertical velocity field at $z = 25$ meters above the surface at $t = 7.6$ hrs with $z_i/L = -10$. Streaky patterns aligned with the surface winds are the dominant coherent structure.

the atmospheric stability approaches the neutral case ($z_i/L \rightarrow 0$) streaky structures elongated in the predominant wind direction appear. These are similar to those noted by Moeng & Sullivan (1994) and McWilliams *et al.*(1999). Animations of the flowfields (not shown) further highlight the transition between coherent structure types in the ABL over the period of the simulations.

One of the objectives of our OBL simulations is to investigate the impact of a finite depth water column on the near surface flowfields. In Figure 5, the variation of the mixed layer depth with time for different underlying stratification levels is displayed. These results show that, as expected, if the stratification is weak ($N < 4.4 \cdot 10^{-3}$) then the OBL will be mixed over the entire water column ($-20 < z < 0$) m in a period of about 6 hours. Also, the presence of wave forcing causes the mixed layer to deepen at a faster rate (*i.e.*, compare the black and red curves in Figure 5). Recall that the present wave forcing is mild and hence appreciably deeper mixed layers might be encountered for stronger wave forcing leading to strong interactions with the bottom boundary. The heat flux profiles in Figure 6 are linear with z and the normalized entrainment fluxes are strongly dependent on the stratification level and the presence of waves. For our OBL simulations the surface heat flux is very small (the OBL is near neutral flow) and consequently the heat flux profiles are dominated by entrainment dynamics and wave forcing. These results are in contrast to the convectively driven ABL which typically has a normalized entrainment flux, $\overline{w\theta}_{min}/q_* \approx -0.2$ for nearly all stratification levels (*e.g.*, Sullivan *et al.*, 1998). Further research is needed to examine the consequences of a finite depth water column on the OBL motions.

IMPACT/APPLICATIONS

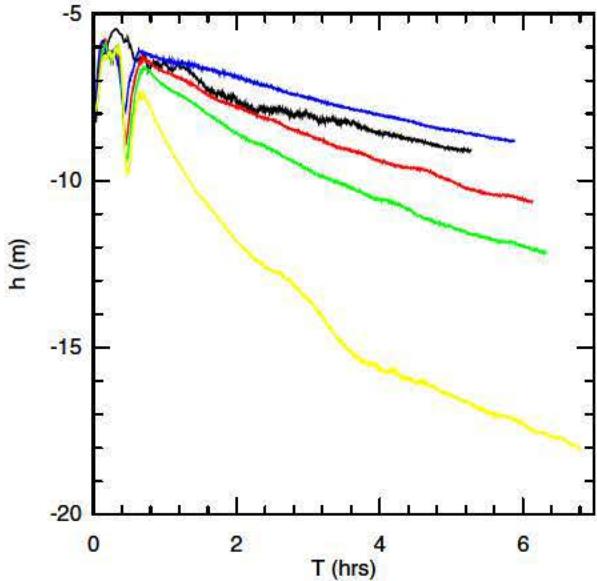


Figure 5: Variation of ocean mixed layer depth with time for varying stratification N . All runs have $\text{Lat} = 0.5$ except for the black line which has $\text{Lat} = \infty$ (no wave effects). $N = [2.2, 1.4, 1.4, 1.0, 0.44] \cdot 10^{-2} \text{ s}^{-1}$ for [blue, black, red, green, yellow] lines, respectively.

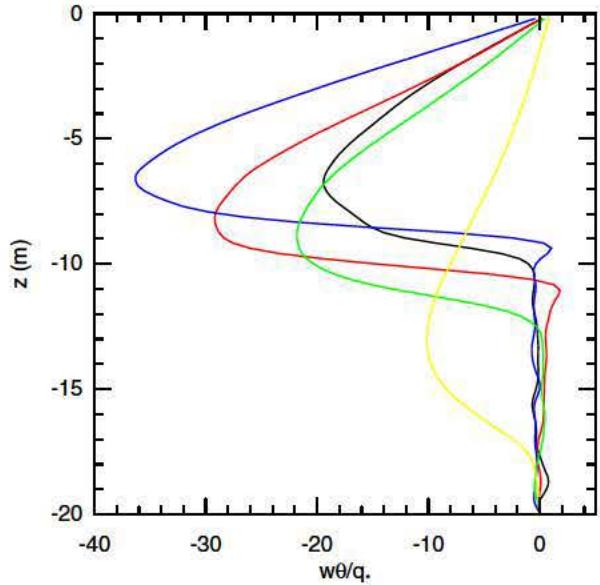


Figure 6: Vertical profiles of normalized heat flux for varying stratification for the same conditions as in Figure 5 at $t \approx 4.8$ hrs. The water column is 20m deep at the CBLAST low-wind site.

Based on these results, we expect atmospheric stability to significantly impact the turbulence and flow structures at the CBLAST low-wind site even in low winds. These simulations can be used to further improve surface and entrainment flux parameterizations for ABLs driven by both shear and convection. The OBL simulations indicate that for some stratifications the OBL can be mixed over the entire water column and hence the presence of a bottom boundary is potentially important. Entrainment at the base of the OBL is strongly influenced by surface wave forcing.

TRANSITIONS & RELATED PROJECTS

In related efforts, two divisions at NCAR (Mesoscale & Microscale Meteorology and Atmospheric Technology) along with Johns-Hopkins University collaborated on a field project in the central valley of California during September through October of 2001. The focus of this field campaign was the measurement of SGS fluxes in the atmospheric surface layer over a range of stability conditions using horizontal arrays of sonic anemometers

(see <http://www.atd.ucar.edu/sssf/projects/sgs2000/> for photographs of the field site and instrument deployment). Extensive data analysis is currently in progress. These measurements are being used to study the dynamics of spatially filtered small scale turbulence and highlight the shortcomings of current SGS models in LES. Similar measurements are being proposed as part of the CBLAST low-wind field campaign planned for the summer of 2002. The interaction between waves and SGS motions and the consequences for LES will be examined in detail. As part of this effort a workshop, sponsored by the Geophysical Turbulence Program at NCAR, entitled “New Developments in Sub-Filter-Scale Closures” is scheduled for August 2002 in Boulder, CO.

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